Multiscale Hyperspectral Imaging of the Orange Hill Porphyry Copper Deposit, Alaska, USA, with Laboratory-, Field-, and Aircraft-based Imaging Spectrometers


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ABSTRACT

In the past decade, use of hyperspectral imaging (imaging spectroscopy) for mineral exploration and mining operations has been increasing at different spatial scales. In this paper, we focus on recent trends in applying imaging spectrometer data to: 1) airborne imaging of high latitude deposits, 2) field-based imaging of outcrops, and 3) laboratory-level imaging of geologic samples. Comparing mineral information derived from imaging spectrometer data acquired at these three scales in Alaska in areas of exposed porphyry Cu-Au-Mo deposits, Orange Hill and Bond Creek, we find notable consistency in identifications of spectrally predominant minerals, including white mica, chlorite, clays, and gypsum. Variations in the wavelength position of white mica 2200 nm Al-OH absorption seen at the airborne level are echoed by finer-scale field and laboratory imaging, with wavelength positions spanning the 2199 to 2207 nm range. The longer wavelength micas associated with porphyry formation are more phengitic in composition, and thus distinct from mica in plutonic and volcanic arc rocks not affected by magmatic-hydrothermal fluids. The hillside imagery, collected on a cloudy day that would have precluded aircraft survey, gave comparable result to airborne and laboratory data, indicating field-based imaging spectroscopy can be a feasible alternative to airborne survey for accessible targets. Direct spectral observation of molybdenite in rocks collected from the Orange Hill deposit demonstrates that additional important mineral information can be revealed with laboratory level imaging spectroscopy that is difficult to obtain in coarser scale data, commonly due to low areal extent of target minerals. The spatial association of the clinochlore + white mica and long wavelength white mica spectral classes to multi-element Cu-Mo-Au anomalies from geochemical analyses of rocks and sediments support a causative relationship with magmatic-hydrothermal alteration. Mineral maps from the airborne data were used to guide field sampling that found additional Cu-Mo-Au mineralized areas, which were previously unknown or unreported. The results from this study provide support for utilization of imaging spectroscopy for assisting mineral exploration in other portions of the state of Alaska as well as other areas at high latitudes. Imaging spectroscopy has the potential to provide targeting information for follow-up sampling and investigations, potentially reducing subsequent exploration costs.

INTRODUCTION

For nearly four decades, the use of airborne imaging spectroscopy for geologic and mineral deposit investigations has primarily focused on visible to shortwave infrared (400 to 2500 nm) reflectance data at well-exposed, mid-latitude sites at local scale (Coulter et al., 2007; Cadahy, 2016; Goetz, 2009; van der Meer, et al., 2012, Swayze et al., 2014). While not effective in identifying many rock forming minerals such as quartz, feldspars, and pyroxenes, the shortwave infrared (SWIR) region (1000–2500 nm) is key to identifying carbonates and hydrous minerals (e.g., micas and clays; Clark, 1999; Thompson et al., 1999; Clark et al., 2003) that are often products of hydrothermal alteration. Airborne imagery is now being collected in new areas across the globe. Applications have been expanding to higher latitudes in Canada (Laakso et al., 2016; Rogge et al., 2014), Greenland (Bedini, 2009 and 2012; Tukiainen and Thomassen, 2010), Alaska (Kokaly et al., 2016; Graham et al., in press), and Antarctica (Black et al., 2016). Significant potential exists for the discovery of economic mineral resources at high latitudes, driving continued exploration activities (e.g., Freeman et al., 2015; Athey et al., 2016). However, the extensive area to evaluate with a lack of infrastructure, coupled with a relatively short summer field season, occasional rugged terrain, and vegetation cover hamper the effectiveness of these activities. New methods such as imaging spectroscopy could greatly aid assessment of large regions to select targets for follow-up ground-based mineral exploration.

In contrast to the longer history of airborne remote sensing, fine spatial resolution imaging spectroscopy for geologic materials in a laboratory setting, or at least in a controlled indoor environment, has only been widely applied in the last decade. Nevertheless, use of fine-scale imaging spectroscopy has expanded quickly with increasing publication of interpretations based on such data in the scientific literature (e.g., Fox et al., 2017; Greenberger et al., 2015; Tappert et al., 2015; Turner et al., 2017). A number of companies offer imaging services for drill core (e.g., Corescan® and TerraCore™, among others) or sell hyperspectral imagers that can be used flexibly in the field or indoors to scan geologic
materials (e.g., Headwall Photonics, Inc., Norsk Elektro Optikk AS, and SPECIM, Spectral Imaging Ltd.). Imaging spectrometers are sometimes packaged with robust translation platforms to scan drill core on an operational basis (e.g., suisRock, Gilden Photonics). Prior to development of imaging systems, spectral interpretation of drill core was done with the Hylologger™ profiling system having a swath of just a single pixel (~8 mm field of view) collected continuously along the length of a drill core (e.g., Arne et al., 2016; Haest et al., 2012a, 2012b; Huntington et al., 2006; Schodlok et al., 2016). In contrast to imaging and profiling systems, spectral studies of core began with and still continue to be conducted with point-based spectrometers applied periodically down the length of a drill core (e.g., Calvin and Pace, 2016; Harraden et al., 2013; Kerr et al., 2011; Kruse, 1996; Ross et al., 2013).

Close range imaging of outcrop and mine surfaces with field-based imaging spectrometers can deliver mineral information with centimeter spatial resolution, which could be used to guide field sampling in exploration and to assess open pit bench faces (Boesche et al., 2015; Buckley et al., 2013; de Linaje and Khan, 2017; Fraser, et al., 2006; Kurz et al., 2008, 2012 and 2013; Murphy and Monteiro, 2013; Murphy et al., 2014). This level of application is currently less developed compared to airborne and laboratory based imaging; however, an increasing number of companies are selling imaging spectrometers at relatively affordable prices compared to a decade ago. As a result, imaging spectrometers are gradually being acquired and utilized by government agencies, academic research institutions, and industry.

Though infrequently collected, imaging spectrometer data sets spanning the three spatial scales of measurement (airborne, field, and laboratory) improve validation and interpretation of mineral maps produced from regional airborne coverage by scaling up results obtained from laboratory analyses. However, there are few examples of studies that compare results from airborne, field and laboratory imaging spectrometers for the same study area (Kruse et al., 2012). More commonly, point-based spectrometers are used at the field and/or laboratory level to support and validate coarser scale imaging spectrometer data (e.g., Laakso et al., 2015; Swayne et al., 2014) or interpretations of laboratory level imaging are extended to airborne hyperspectral or multispectral satellite data (Zhou et al., 2017). With increased application of imaging spectroscopy for drill core and geologic samples (e.g., Martini et al., 2017) and the decreasing cost of field-deployable imaging spectrometers, there is a need to examine how consistent mineral information can be measured across airborne, field and laboratory spatial scales.

In this paper, we examine the application of imaging spectroscopy for mineral exploration in Alaska in areas of exposed porphyry Cu-Au-Mo deposits—Orange Hill and Bond Creek—with an emphasis on comparing the consistency of mineral information derived from three different imaging spectrometers used to acquire airborne, field and laboratory datasets. We demonstrate a linkage between spectral signatures and mapped mineral patterns of Cu-Au-Mo-mineralized areas. Results from field-based imaging of outcrops at the Orange Hill deposit are compared to results from airborne data collected over the deposit and to laboratory-level imaging of rock samples collected from the deposit. Despite the imaging spectrometers having different spatial resolutions (0.5 mm to 6 m), spectral sampling (1 to 20 nm), and bandpass (6 to 20 nm), and vastly different collection conditions (from artificial illumination in the lab to partly-cloudy solar illumination in the field), we generate largely consistent mineral information. Weathered coatings on rocks surfaces imaged from aircraft and in the field did not cause appreciable differences in mapped mineral composition compared to fresh cut surfaces imaged in the laboratory. These results indicate airborne- and outcrop-scale imaging spectroscopy has effective application for mineral exploration at high latitudes.

**ORANGE HILL-BOND CREEK STUDY AREA**

The Orange Hill-Bond Creek study area, which encompasses ~260 km² (~100 mi²), is located approximately 450 km ENE of Anchorage (Figure 1a). Its rugged terrane varies from approximately 900 to more than 2,750 m elevation above sea level. Trees are abundant at lower elevations, but give way to tundra and then largely lichen free outcrop and talus at higher elevations (local tree line is ~1,400 m). The following description of regional and local geology is adapted from Graham et al. (in press). The study area lies within an accretionary belt encompassing the Wrangella island arc terrane and paleocontinental margin, which occurred in the Jurassic to Cretaceous (Plafker and Berg, 1994; see Figure 1b). A discontinuously exposed belt of flysch basins, including the Nutzotin basin, preserved sediments accumulated in the now closed intervening ocean basin (Berg et al., 1972; Goldfarb et al., 2013; Manuszak et al., 2007; Plafker and Berg, 1994). The Orange Hill-Bond Creek study area lies just southwest of the Totschunda fault system that splays off of the Denali Fault. Early Cretaceous plutons intruded both deformed Nutzotin flysch and the nearby leading edge of the exposed Wrangellia terrane. Recent U-Pb age data indicate emplacement between ~126.4±1 and 113±0.5 Ma (Graham et al., 2016). More recent Cenozoic plutonic and volcanic rocks are locally abundant (Richter, 1973).

The geology of the study area includes Early Cretaceous rocks of the Nabesna pluton to the north that are in contact with Wrangella terrane to the south (Figure 1c). The following geologic descriptions of the plutonic and arc rocks are from Richter (1973). The Nabesna pluton consists predominately of biotite hornblende granodiorite with lesser quartz monzonite, biotite quartz diorite, and hornblende diorite. Sparse exposures of medium to coarse-grained trondhjemite and light gray quartz-plagioclase porphyry occur locally. To the south of the roughly east-striking contact, the Wrangella terrane rocks include Pennsylvanian and/or Permian fragmental volcanic rocks, tuffs, and flows of andesitic composition as well as a massive quartz breccia extrusive or shallow intrusive body. Overlying the volcanic rocks are Permian limestone and Permian to Triassic calcareous and carbonaceous siltstone and argillite; the carbonaceous argillite has a basal silicic tuff unit and has locally been intruded by dikes, sills, and irregularly-shaped bodies of Triassic gabbro (forming up to 50% of the stratigraphic section). The Nikolai Greenstone is comprised of amygdaloidal basalt flows with thin interlayered volcanioclastic beds. Amygdaloids are filled with quartz, calcite, chlorite, epidote, pumpellyite, zeolite minerals, and locally, copper.
The Orange Hill and Bond Creek porphyry Cu-Mo(Au) deposits (Figure 2a) are the two best studied porphyry systems in the study area. Orange Hill is a conspicuous iron-stained knob that rises approximately 100 m above the eastern side of the Nabesna Glacier valley and is separated from the higher ridge to the east by California Gulch (Figures 1c and 2a). To the east and north of the higher ridge are the west, middle, and east forks of Bond Creek, which flow north and west. Reported alteration zonation at Orange Hill includes a 400 by 2,000 m zone of potassic alteration (including biotite, quartz veinlets, minor potassium-feldspar, chlorite, and sericite) and an outer 1 by 3 km zone of chlorite and minor sericite (Richter et al., 1975a). Other gangue minerals include calcite and kaolinite (van Alstine and Black, 1943). Due to vegetation, much of this altered rock is not exposed and zonation cannot be observed at surface. However, stockwork quartz-chalcopyrite-pyrite+molybdenite veins are exposed up to 1,400 m to the northeast (Figures 2b and 2c). The Bond Creek deposit is at higher elevation, where outcrop, rubblecrop and talus with minimal lichen cover predominate (Figure 2d). Chalcopyrite ± molybdenite-bearing quartz-rich and quartz-poor veins are present (Figure 2e) and pervasive alteration is evident in both the Nabesna pluton and adjacent Wrangellia terrane volcanic arc rocks (Figure 2d). Richter et al. (1975a) reported the alteration included a central zone with abundant chlorite, minor biotite and potassium-feldspar, where spotty sericite is enveloped in a 2 by 3 km zone with minor chlorite, epidote and anhydrite. Orange Hill and Bond Creek deposits are both cut by late anhydrite veins.
Richter et al. (1975a) estimated 320 Mt of rock with an average grade of 0.35 wt% copper at Orange Hill and 500 Mt of rock with 0.3 wt% Cu at Bond Creek. Both deposits were estimated to contain 0.02 wt% Mo, with some elevated gold. Several other porphyry prospects, skarn, and polymetallic veins have been identified in the study area, but have not been extensively described (Hudson, 2003; Richter et al., 1975a).

METHODS

Our study examines airborne-, field-, and laboratory-based imaging spectrometer data integrated with field and laboratory-based geologic investigation. The following description of methods parallels the methods described in Graham et al. (in press), with added description of field-based imaging and spectral analysis. Complete spectral and geochemical results can be found in the USGS ScienceBase Data Releases Graham et al. (2017), Hoefen et al. (2018), and Kokaly et al. (2017a and 2018).

Spectral Data Collection and Conversion to Reflectance

A total of 1,900 km² of imagery (Kokaly et al., 2017a) were collected on July 14 and 21, 2014 using a HyMap sensor (Cocks et al., 1998). The Orange Hill-Bond Creek study area lies in the western portion of the imaged area. HyMap was mounted on a modified Piper Navajo aircraft flown at an altitude of approximately 3,480 m above the mean ground surface elevation of 1,570 m. HyMap measured reflected sunlight in 126 narrow channels (Table 1). Collected images had a nominal pixel size of approximately 6 m. Data were delivered by the operators of the sensor (HyVista Corp., Australia) in units of radiance and converted to reflectance with procedures adapted from Kokaly et al. (2013). First, the radiance data were converted to apparent surface reflectance using radiative transfer programs. Two programs were tested: Atmospheric CORrection Now (ACORN) version 6lx (ImSpec LLC, Palmdale, California, USA), and Atmospheric and Topographic Correction for airborne imagery (ATCOR-4) in rugged terrain mode (ReSe Applications, Zurich, Switzerland). The ATCOR-4 rugged terrain mode utilizes a surface elevation model to adjust illumination levels, which produced more realistic reflectance levels in steep, north-facing terrain with little or no direct solar illumination than ACORN results. Subsequently, apparent surface reflectance values from the ATCOR-4 processing were empirically adjusted using ground-based reflectance measurements from calibration sites measured with an Analytical Spectral Devices FieldSpec® 4 standard resolution field spectrometer (ASD F4; see below).

On July 10, 2015, a tripod-mounted, field-based HySpex™ SWIR-384me hyperspectral camera (HyLab, University of Alaska Fairbanks; www.hyperspectral.alaska.edu) covering the SWIR wavelength region, hereafter referred to as HySpex imaging spectrometer, was used to scan a Cu-Mo-Au mineralized outcrop on the western side of Orange Hill (Figure 1c). Sky conditions were partly to mostly cloudy during the two hour collection session. The scanned hillside, approximately 1,000 m wide and 100 m high, was imaged with approximately 30 cm pixel size from a position 350 m from the base of the hill. Eight scans were made of the hillside during brief periods when the sun was not obscured by clouds. In the SWIR region, HySpex spectral data have much higher spectral detail (a greater number of channels with finer sampling interval and spectral bandpass) compared to the airborne HyMap instrument (see Table 1).
HySpex ground-based data were converted from raw sensor response to radiance using the manufacturer supplied sensor response functions, which were developed by recording HySpex raw sensor output while observing a calibrated integrating sphere with known lamp illumination. To convert the radiance data to reflectance, an empirical line correction method for imaging spectrometer data was used (Conel et al., 1987). ASD FS4 measurements of two areas in the HySpex scene were collected contemporaneous with the imagery for use as the dark and light target spectra in the empirical line correction method. Each of the eight scans made of the hillside were independently converted to reflectance. Six of the eight datasets were largely free of water-related atmospheric artifacts and were averaged together to increase their signal-to-noise ratio (SNR). The radiance level of the scene was low, in particular at the longer wavelengths. For example, the radiance level was 1.02 mW/m²/sr/nm at 2350 nm, which is only a tenth of a typical radiance level of bright targets at mid-latitude in mid-summer (for comparison see the radiance spectra in Green et al., 1998). Pixel averaging (spatial averaging) increases SNR as a function of the square root of the number of pixels averaged. A 3 x 3 pixel averaging was performed to increase the SNR by a factor of 3 before mapping spectrally predominant minerals. A 5 x 5 pixel averaging was applied to boost SNR by a factor of 5 to increase accuracy of the white mica wavelength position determination.

A Corescan Hyperspectral Core Imager Mark III™ imaging spectrometer (http://www.corescan.com.au/services/corescan-system) hereafter referred to as Corescan imaging spectrometer, was used to scan approximately 50 rock samples collected from the Orange Hill and Bond Creek deposits during the summer of 2015 (Hoefer et al., 2018). Four thin sections were cut from selected portions of three hand samples in areas of predominant white mica. The billets, from which the thin sections were cut, were also scanned. Fresh cut surfaces of rocks and billets were imaged at a spatial resolution of approximately 0.5 mm for 514 spectral channels spanning the 450–2500 nm wavelength range (see Table 1). Corescan delivered the spectral data in reflectance.

Point-based spectral collections were completed using an ASD FS4 field spectrometer (see its spectral characteristics in Table 1) in order to calibrate both ATCOR-4 corrected HyMap data and HySpex radiance data to reflectance. For the HyMap data, reflectance spectra were collected from four calibration sites in broad alluvial-fluvial gravel bars that were minimally vegetated and essentially lichen-free. The average relative reflectance of each site was converted to absolute reflectance by correcting for detector offsets and the absorption properties of Spectralon (see Kokaly and Skidmore, 2015) using a procedure in the U.S. Geological Survey (USGS) PRISM (Processing Routines in IDL for Spectroscopic Measurements) software (Kokaly, 2011). PRISM is a freely distributed software (https://speclab.cr.usgs.gov/spectral-lib.html/software) programmed in Interactive Data Language (IDL; Harris Geospatial Solutions, Broomfield, Colorado, USA). A PRISM function was used to compute multiplicative correction factors to convert HyMap apparent surface reflectance (resulting from ATCOR-4 processing) to radiative transfer ground-calibrated (RTGC) reflectance (Kokaly et al., 2013). Because flight lines were designed with substantial overlap, the four calibration sites could be used to directly calibrate eight of the nine flight lines. For the remaining flight line, the cross-calibration procedure of Kokaly et al. (2013) was used to compute an empirical correction factor using a non-vegetated and topographically flat area overlapped by an adjacent, ground-calibrated flight line.

**Spectrometer Data Accuracy**

The wavelength and bandpass characteristics of each spectrometer used in this study were evaluated using a set of reference materials (see descriptions of the evaluation procedure in Kokaly et al., 2018; Graham et al., in press). ASD, HyMap and HySpex evaluations agreed with manufacturer reported values (see spectral characteristics in Table 1). For the Corescan imaging spectrometer, two evaluations were conducted. The first was applied to processed data of the reference standards made contemporaneous with the scans of the rock samples. An effective bandpass of 13 nm was calculated for the 2000–2500 nm region. A subsequent data collection was performed solely for the purpose of measuring the reference standards. The second evaluation, applied to raw data, showed the Corescan imaging spectrometer collected data with an average bandpass of approximately 6 nm across the SWIR. The discrepancy between evaluations was determined to be a result of smoothing functions.

<table>
<thead>
<tr>
<th>Spectrometer</th>
<th>Type</th>
<th>Collection level</th>
<th>Spectral range (nm)</th>
<th># of spectral channels</th>
<th>Sampling interval (nm)</th>
<th>Average bandpass VNIR (nm)</th>
<th>Average bandpass SWIR (nm)</th>
<th>Spatial pixel size</th>
</tr>
</thead>
<tbody>
<tr>
<td>HyMap</td>
<td>Imaging</td>
<td>Airborne</td>
<td>455-2483</td>
<td>126</td>
<td>16.2</td>
<td>16.1</td>
<td>16.7</td>
<td>6 m</td>
</tr>
<tr>
<td>HySpex SWIR-384</td>
<td>Imaging</td>
<td>Field</td>
<td>949-2508</td>
<td>288</td>
<td>5.4</td>
<td>not applicable</td>
<td>7</td>
<td>30 cm</td>
</tr>
<tr>
<td>Corescan Hyperspectral Core Imager Mark III™</td>
<td>Imaging</td>
<td>Field</td>
<td>448-2500</td>
<td>514</td>
<td>4</td>
<td>5.5 for raw data 13 for smoothed</td>
<td>5.2 for raw data 10.8 for smoothed</td>
<td>0.5 mm</td>
</tr>
<tr>
<td>Analytical Spectral Devices FieldSpec® 4</td>
<td>Point</td>
<td>Field</td>
<td>350-2500</td>
<td>2,151</td>
<td>1*</td>
<td>5.2</td>
<td>11.5</td>
<td>~50 cm**</td>
</tr>
</tbody>
</table>

*interpolated from native sampling interval ~2 nm

**average value for fiber optic held at shoulder height, area of each measurement varied with distance between fiber optic and surface

Table 1: Spectral and spatial characteristics of spectrometer data collected for the Orange Hill-Bond Creek study.
applied during the processing of raw data to reflectance. Both evaluations of the Corescan imaging spectrometer revealed that supplied wavelength values should be adjusted (see Hoefen et al., 2018). In the wavelength region of the white mica absorption feature centered near 2200 nm, wavelength positions of the Corescan imaging spectrometer channels were shifted ~1.4 nm on average to longer wavelength. The adjustments to the supplied wavelength values were made before mapping spectrally predominant minerals and computing white mica wavelength positions.

Knowledge of wavelength and bandpass characteristics permitted mathematical convolution of the higher (finer) resolution ASD spectra to ground-calibrate the coarser resolution HyMap imaging spectrometer data, using a function of the PRIS software (Kokaly, 2011). This step was necessary before computing the RTGC multiplier correction. Wavelength and bandpass values were also required to convolve finer sampled, higher resolution reference spectra to the coarser spectral characteristics of the HyMap, HySpex and Corescan imaging spectrometers in order to make mineral predominance maps. We utilized the calculated value of 13 nm as the effective bandpass in order to convolve reference spectra and map the spectrally predominant minerals in the Corescan data cubes.

### Spectrally Predominant Mineral Classification

Reflectance data from the imaging spectrometers were processed using the Material Identification and Characterization Algorithm (MICA), a module of the PRIS software (Kokaly, 2011) that is similar to the USGS Tetracorder expert system (Clark et al., 2003). MICA identifies the spectrally predominant mineral(s) in each pixel of a data cube by comparing continuum-removed spectral features in its reflectance spectrum to continuum-removed absorption features in reference spectra of minerals, vegetation, water, and other materials. The term spectrally predominant mineral in this paper is used to indicate the mineral with the highest importance/greatest influence on the reflectance spectrum, following the terminology of Kruse et al. (1993) that is commonly found in the terrestrial remote sensing literature. Linear continuum removal is a technique to isolate an absorption feature from background spectral variations (Clark and Roush, 1984; Clark, 1999). Following continuum removal of a spectral feature in a reference spectrum and the corresponding channels in an imaging spectrometer pixel, the coefficient of determination ($r^2$) of a linear regression of these continuum-removed values is used as the metric to judge the degree of match (or fit) between the two spectra. MICA analysis is controlled by a command file, which lists the reference spectra for comparison to imaging spectrometer pixels, the wavelength regions for continuum removal and spectral feature comparison, and other parameters (see Kokaly, 2011). For each pixel, the reference spectrum with the highest fit value is assigned as the predominant mineral class. The MICA command file used in this study was adapted from that used to process HyMap coverage of Afghanistan (Kokaly et al., 2013), with several mineral reference spectra added and continuum endpoints adjusted for the HySpex and Corescan imaging spectrometers (see the MICA command files in Kokaly et al., 2018; Hoefen et al., 2018).

Although spectral analysis in the SWIR range is effective at identifying the presence of a number of minerals, spectral features of certain minerals or combinations of minerals are similar enough to preclude definitive distinction at the coarse spectral resolution of the HyMap airborne data. For example, spectra of muscovite and illite can have similar absorption features, dependent on mineral chemistry (Swayze et al., 2014). As a result, we collectively refer to pixels matching any of the reference spectra of muscovite and illite as white mica. The reference spectra used in this study are available to the public in the USGS spectral library (Kokaly et al., 2017b). Individual output for the 77 entries in the MICA command file were combined into the grouped classes depicted in mineral predominance maps (for Kokaly et al., 2018).

### Mineral Composition Mapping

Subtle changes in SWIR absorption feature positions can provide evidence of compositional variations in some minerals, in particular white micas (Swayze et al., 1992; Post and Noble, 1993; Swayze et al., 2014). Examples of previous studies include spectral mapping of muscovite and/or chlorite of varying compositions to characterize metamorphic history (e.g., Duke, 1994) and geology and zoning about mineral deposits (e.g., Herrmann et al., 2001; van Ruitenbeek et al., 2012; Harraden et al., 2013; Swayze et al., 2014, Laakso et al., 2015). In this study, the wavelength position of the white mica 2200 nm absorption feature was computed for any pixel that was found to have the highest fit to muscovite or illite reference spectra in the MICA analysis. After continuum-removal of this feature, we fit a parabola to three channels: the channel with the minimum value in continuum-removed reflectance and one channel on either side of the fitted parabola as the definition of the wavelength position of the white mica 2200 nm Al-OH absorption feature (hereafter referred to as the white mica wavelength position). The images of continuous values of wavelength position were converted to classification images with classes in 1 nm increments.

The fitted parabola provides a modeled position for the relatively coarser sampling intervals and bandpasses of imaging spectrometers (e.g., 6.5 to 20 nm) that is closely comparable to positions measured by point-based laboratory spectrometers with fine sampling and bandpass (e.g., ≤1 nm sampling interval of the library reference spectra). Using 23 muscovite and illite spectra in the USGS Spectral Library Version 7 (Kokaly et al., 2017b), we compared white mica wavelength positions in the finely sampled reference spectra to positions computed after convolution to HySpex, Corescan, and HyMap imaging spectrometer characteristics. The convolved-to-HySpex spectra had the lowest overall difference in wavelength position compared to the original reference spectra with only a 0.2 nm average shift to shorter wavelengths. The feature positions in the spectra, after convolution to Corescan imaging spectrometer resolution, were shifted on average 0.3 nm to shorter wavelengths. The convolved-to-HyMap spectra, with relatively coarse 18.5 nm sampling interval and bandpass in the 2200 nm region, had an average shift of 1.2 nm to shorter wavelengths. This evaluation shows that white mica wavelength positions from the three imaging spectrometers used in this study are theoretically comparable within ~1 nm.
Sediment/Soil/Rock Chemistry and Mineralogy

Geologic samples were collected at and around mineral occurrences and used for additional laboratory-based analyses, including imaging spectroscopy and geochemical characterization. The samples were used to characterize specific mineral deposit and prospect areas, fill in gaps in sample coverage, and follow up on observed spectral anomalies. Sediment data from the Alaska Geochemical Database (Granitto et al., 2011) were used to establish the regional geochemical framework. As described by Graham et al. (in press), we collected an additional 96 rock and 66 soil and sediment samples for geochemical analysis to obtain concentrations of 55 major, rare earth, and trace elements by inductively coupled plasma-atomic emission spectrometry-mass spectrometry (ICP-AES-MS) after sodium peroxide fusion. Gold was determined by fire assay. Threshold concentrations, above which elements are considered anomalous, were chosen based on multiples of the median abundance values for soil samples collected throughout the conterminous United States (Smith et al., 2013). These threshold values were applied to both historic data sets and our new geochemical dataset. Select soil and rock samples were also analyzed by x-ray diffraction (XRD) to validate the presence of spectrally identifiable minerals found in mineral predominance maps by MICA analysis. XRD results for representative samples are presented in the digital appendix Table A2 of Graham et al. (in press) and Graham et al. (2017).

White Mica Chemistry

Electron probe microanalysis (EPMA) using five wavelength dispersive spectrometers was completed on white mica and lesser chlorite and kaolinite using a JEOL JXA-8900 Superprobe at the USGS Central Mineral and Environmental Resources Science Center, Denver, CO, USA. The microanalyzer was operated at 15 kV and 20 nA, with a beam diameter of less than 1 μm. Calibration was checked using well-characterized silicate and oxide standards. Data for EPMA results are available in Graham et al. (2017). In this paper, EPMA results for white mica Al composition are related to white mica wavelength position from the Corescan imaging spectrometer data.

RESULTS

Airborne Imaging Spectroscopy and Patterns Related to Mineral Occurrences and Geochemistry

Results of mapping for spectrally predominant minerals and white mica wavelength position are shown in Figures 3 and 4, respectively. These figures were adapted from Graham et al. (in press). At the deposit scale, distributions of spectrally predominant minerals reflect both lithology and magmatic-hydrothermal overprinting. In the Bond Creek deposit area, a >1.5 x 2 km zone dominated by white mica and lesser clinochlore+white mica signatures (encompassed by thick, black, dotted line around location 2 in Figure 3) closely corresponds to the altered zone mapped by Richter (1973). The zone grades northward to clinochlore+white mica and then clinochlore+white mica with irregular chlorite/clinochlore/epidote and carbonate signatures, perhaps reflecting a phyllic core flanked by chlorite-white mica to propylitic zones. This pattern is consistent with a partially exhumed idealized altered porphyry system (e.g., Lowell and Galibert, 1970; Sillitoe, 2010), although a continuous zone around the suggested phyllic core is not observed due to topographic variations to the east and west where valley bottoms are covered with glacial debris. The predominance of jarosite along with mixed layer clay (illite/smectite) on the steep eastern side of the Bond Creek ridge is conspicuous, with spectrally-detected jarosite likely being an important indicator of weathering of sulfide-bearing rock (Swayze et al., 2000).

Coherent patterns of the three main chlorite-bearing mineral spectrally predominant classes (i.e., chlorite/clinochlore/epidote, clinochlore+white mica, and chlorite+white mica, see bright red, dark red, and dark orange colors, respectively) strongly support fundamental differences in chlorite composition or relative proportions of chlorite and white mica related to lithology or magmatic-hydrothermal processes. The distribution of chlorite/clinochlore/epidote pixels in Nikolai Greenstone and widespread clinochlore+white mica pixels in the volcanic and volcaniclastic rocks of the Wrangellia terrane suggest lithological control (Figure 3). In contrast, the distribution of the clinochlore+white mica class was inferred by Graham et al. (in press) to be related to magmatic-hydrothermal processes based on 1) close spatial association to the porphyry cluster in the Nabesna pluton, 2) extension across lithologic boundaries at the Bond Creek deposit, and 3) the near absence of this (or any chlorite-dominated) class elsewhere in the Nabesna pluton.

The majority of white mica displays Al-OH absorption at wavelength positions less than 2202 nm (blue and purple in Figure 4). Overall, intermediate to longer wavelength absorption-bearing white mica has similar but broader distribution when compared to that of the clinochlore+white mica class. Concentrations of longer-wavelength white mica (i.e., green, yellow and red pixels) are in the Nabesna pluton, extending from the Orange Hill area (location 1 in Figure 4), through Bond Creek (location 2; Figure 4) to east of the Middle Fork of Bond Creek and north to the East Fork of Bond Creek. This signature incorporates the Nike and Neil porphyry prospects (locs. 3 and 4; Figure 4) and the vicinity of the unnamed porphyry Mo prospect (location 5; Figure 4). At the Bond Creek deposit, rocks with white mica at longer wavelength positions extend into the Wrangellia terrane volcanic rocks. Some intermediate to longer wavelength signatures (≥2203 nm) were also detected in the vicinity of the Copper King skarn (location 6; Figure 4). Long wavelength white mica signatures also occur north of the East Fork of Bond Creek and at the headwaters of the East Fork (locs. 7 and 8; Figure 4), in areas dominated by clinochlore+white mica pixels (Figure 3). A narrow, but prominent zone of longer wavelength white mica (location 10; Figure 4) is present in a small drainage SW of location 7. In the volcanic rocks to the south, zones of intermediate to long wavelengths are present, but primarily encompass only small isolated areas. The most extensive zone is on the southern edge of our survey on the West Fork of Bond Creek (location 9; Figure 4) and coincides with clinochlore+white mica signatures (Figure 3). This area is at the toe of a glacier and could be from eroded rocks transported from the south, where an undifferentiated mafic intrusion, interpreted as a probable marginal phase of the Nabesna pluton, is exposed (Richter, 1973).
Figure 3: Regional mineral predominance map derived from HyMap imaging spectrometer data for the Orange Hill-Bond Creek area. Full resolution results were processed with a 3 x 3 pixel majority filter to highlight the mineral class differences at this scale. In the Bond Creek deposit area a central zone (encompassed by thick, black, dotted line around location 2) is dominated by white mica and lesser clinochlore+white mica signatures, closely corresponding to the altered zone mapped by Richter (1973). Figure adapted from Graham et al. (in press).

The spatial association of the clinochlore+white mica and long wavelength white mica classes with multi-element Cu-Mo-Au anomalies (magenta dots in Figure 4) was found by Graham et al. (in press) to support a causative relationship with hydrothermal activity. The linkage of long wavelength signatures in Corescan imaging spectrometer data with more phengitic chemistry in microprobe analyses (see results below) suggests the longer wavelength white mica is of magmatic-hydrothermal origin. At the Bond Creek deposit, anomalous concentrations of Cu, Mo, and Au occur in the upstream portion of the West and Middle...
Forks of Bond creek in the immediate vicinity of longer wavelength white mica. Where this zone extends to the east across the Middle Fork of Bond Creek, metal concentrations remain high (e.g., location 4b, Figure 4). The mixed spectral signatures at Orange Hill (location 1) and the gullies to the northeast have highly anomalous metals concentrations. The absence of significant clinochlore+white mica and long wavelength white mica signatures in most of the Wrangellia terrane rocks coincide with a general lack of anomalous multi-element Cu-Mo±Au concentrations (small white dots on Figure 4). Only sporadic Cu anomalies are present and could be related to an abundance of mafic rock (inherently higher Cu concentrations) and weathering of the Nikolai Greenstone (Richter, 1973).

Several zones outside of the Cu cluster of the main porphyry that have long wavelength white mica and clinochlore+white mica also contain anomalous Cu, Mo and/or Au (locations 7, 8, and 10 in Figures 3 and 4). These areas were sampled in follow-up field work in 2016 after initial interpretation of the spectrally predominant mineral and white mica wavelength maps. Some rock samples from these locations contain up to 8,000 ppm Cu >50 ppm Mo, and >500 ppb Au, with visible sulfide veins and disseminations. Thus, the spectral maps were instrumental in finding additional Cu-Mo-Au mineralized areas that were previously unknown or unreported. Beyond the bounds of this study area but within the full coverage of HyMap data (Kokaly et al., 2017a and 2018), additional clinochlore+white mica and

![Figure 4](image-url): Regional map of white mica wavelength position derived from HyMap airborne imaging spectrometer data. Warmer colors (green, yellow, orange and red) show the distribution of pixels with white mica having longer wavelength absorptions. Longer wavelength zones include a broad area within the porphyry Cu cluster and several satellite zones. Numbered areas are discussed in the text. The area shown in this figure is approximately the same as Figure 3. Adapted from Graham et al. (in press).
longer wavelength white mica signatures were found near bedrock occurrences of pyrite and chalcopyrite mineralization in the vicinity of Gold Hill (62.0809° N, 141.8674° W). Polymetallic veins at Johnson Creek, Chathenda Creek, Erie, and other unnamed mineral occurrences nearby are likely related to the mid-Cretaceous emplacement of the Chisana pluton (Richter et al., 1975b; U.S. Geological Survey, 2012).

**Airborne Imaging Spectroscopy at Orange Hill**

Large-scale zoning patterns are not obvious within the Orange Hill deposit owing to extensive vegetative cover. However, a geologic map of the deposit (Linn, 1973) indicates at least three phases of the Nabesna pluton at Orange Hill: a diorite body in the southwestern part of the hill in contact with the locally dominant tonalite on the northern and eastern parts and quartz-feldspar porphyry exposed in the headwaters of California Gulch (Figure 5). Spectrally, clinochlore+white mica signatures are widespread in the diorite (and some adjacent tonalite), mixed layer clay (illite/smectite) and gypsum occur in the more weathered tonalite on the northwest side of the ridge, and kaolinite and white mica signatures predominate at and around quartz-feldspar porphyry in the headwaters of California Gulch. Kaolinite+white mica signatures to the east by the Copper King skarn coincide with additional quartz-feldspar porphyry (Figure 5). Therefore, as a first order, the spectral signatures at Orange Hill empirically reflect alteration assemblages in different rock units. Graham et al. (in press) further discuss the relation of the spectral signatures to intensity of alteration, relating the mixed layer clay (illite/smectite)-signature in tonalite to more intense alteration than in the dioritic rocks to the southwest. The quartz-feldspar porphyry, lacking mafic minerals and located in the head of California Gulch, has extensive quartz veining indicating widespread hydrothermal fluid circulation. Alteration and weathering of feldspar and mica within this unit and the rocks it intruded produced kaolinite rather than mixed layer clay (illite/smectite) signatures.

Figure 5: Expanded view of the mineral predominance map for the Orange Hill deposit (from Figure 3, but mineral classes are shown without application of 3 x 3 majority filter). White box marks the location of HySpex hillside scan in Figure 6. Superimposed geology is from Linn et al. (1973). Figure adapted from Graham et al. (in press).
Figure 6: Orange Hill area field-based HySpex hillside scan results compared to HyMap airborne data results: a) predominant materials map from HyMap; b) predominant minerals map from HySpex; c) white mica wavelength map from HyMap; d) white mica wavelength map from HySpex. Pixel size in the HyMap images is 6 m. HySpex imagery was collected at 30 cm pixel size, with 3 x 3 pixel averaging applied before mineral predominance mapping and 5 x 5 pixel averaging applied before white mica wavelength mapping. Gray areas in Figure 6b were spectrally matched to vegetation. White mica wavelength position (Figures 6c, 6d) is only depicted for pixels in which white mica (muscovite or illite) was spectrally predominant; difference in white mica wavelength position between HyMap and HySpex is a result of their different spectral characteristics (see text for details). Horizontal striping in Figure 6d is an artifact caused by low signal:noise in the data collection. The area of the HySpex scan is the westernmost exposure of the Orange Hill deposit marked on Figure 5.

Both clinochlore+white mica and kaolinite+white mica zones are also mapped in the mineralized drainages to the northeast of Orange Hill, and similarly reflect different variably altered and mineralized dioritic to granodioritic rocks. Importantly, the abrupt change in spectral signatures in the drainages aligns with, and thus locally defines the Bryner fault (Figure 5). The predominance of chlorite, epidote, and carbonate signatures in plutonic rocks farther uphill to the east may reflect distal propylitic alteration associated with the Orange Hill porphyry system.

Field-based Imaging Spectroscopy at Orange Hill

The spectrally predominant minerals in the HySpex hillside image match the HyMap results, namely, white mica, clinochlore+white mica, mixed layer clay (illite/smectite),
kaolinite, and gypsum (Figure 6a). However, the proportions of areas mapped as various classes differ. In the hillside scan more mixed layer clay (illite/smectite) and less gypsum are identified compared to the HyMap result. To examine whether the difference was a result of spectral and spatial differences between the two spectrometers, the HySpex images were resampled to the coarser HyMap spectral characteristics and 6 m pixel size of the airborne data. The mineral predominance map from the spectrally and spatially resampled HySpex data was similar to the original mineral predominance map generated from the HySpex scan. The differences in mineral proportions, which were not explained by sensor spectral/spatial resolution, could be the result of changing view position between the airborne and field measurements, i.e., observing from an overhead position (HyMap) compared to scanning from the side (HySpex).

Figure 7: Corescan imaging spectrometer results for rocks collected in the Orange Hill area: a) mineral predominance map; b) white mica wavelength map. Sample collection localities are indicated in Figure 5. Sample names in yellow indicate rocks from which thin section billets were cut (see Figure 8).
The HySpex map of white mica wavelength position shows slightly longer wavelength positions, most ranging from 2203 to 2206 nm, in comparison to the HyMap results with pixels ranging from 2202 to 2205 nm (Figure 6b), an apparent 1 nm difference that is a consequence of the dissimilarity in bandpass between the two sensors shifting the HyMap-derived white mica positions 2 nm to shorter wavelength on average (as discussed previously in the Methods section). Across the face of the hillside, both results show shorter wavelength positions in the southern region of the hill (see the cooler colors, blue tones, on the right portion of images in Figure 6b).

Figure 8: Corescan imaging spectrometer results for billets cut from rocks collected at Orange Hill, image pair shows the mineral predominance map (top) and white mica wavelength position map (bottom). Locations of cuts for billet/thin section are marked on the rocks. Locations at which wavelength determinations were made corresponding to the electron probe microanalyses (EPMA) are marked with circles.
Laboratory Imaging Spectroscopy of Rock Samples Collected at Orange Hill

The mineral maps produced from the Corescan imaging spectrometer data for the hand specimens (22 samples collected from Orange Hill and two from Bond Creek) identify spectrally predominant minerals that are equivalent to the HySpex and HyMap results for the Orange Hill area, specifically, white mica, clinochlore+white mica, clinochlore/chlorite/epidote, mixed layer clay (illite/smectite), kaolinite, and gypsum (Figure 7a). The corresponding white mica wavelength position maps (Figure 7b) show that white mica wavelengths in the rocks range from ≤2199 to ≥2207 nm. This range is broader than that observed in the HySpex and HyMap data for Orange Hill. Possibly, mixing of signatures at coarser spatial scales effectively averages the wavelength positions to a more compressed range. Some rocks have consistent white mica positions throughout, at shorter wavelengths (e.g., 14HYPORH015 and 15HYPORH008) or longer wavelengths (e.g., 14HYPORH001, 15HYPORH006e, and 15HYPBDC055). Others show variation in wavelength position within individual rocks (e.g., 14HYPORH013a, 15HYPORH002, and 15HYPORH025).

Shifts in the white mica wavelength positions of the 2200 nm Al-OH absorption features have been related to Al in the octahedral site of the muscovite mineral structure (A$^{\text{oct}}$; e.g., Post and Noble, 1993; Yang et al., 2001; Swayze et al., 2014; Yang et al., 2011). In order to test that compositional relationship for white mica at the Orange Hill deposit, four billets were cut from the rock samples and then scanned with the Corescan imaging spectrometer. Two of the billets have cut areas with the same wavelength positions (14HYPORH013a-Billet 1 and 15HYPORH006e-Billet 4) and two have variations in wavelength position (14HYPORH013a-Billet 2 and 15HYPORH002-Billet 3). Figure 8 shows the mapping results for the four selected billets, along with locations on matching thin sections that were analyzed using EPMA (locations were not marked for 14HYPORH013a-lower because of the consistently long wavelength position across the billet). Graham et al. (in press) examined the relationship of wavelength and chemical composition based principally on wavelength classes for two groups (shorter wavelength ≤2203 nm and longer wavelength ≥2207 nm), finding higher median Si, Mg, and Mn and lower median Al (±Na) concentrations in the white mica with longer as compared to shorter wavelength positions. There is a systematic inverse relationship attributed to Tschermak substitution (A$^{\text{oct}}$ + Al$^{\text{tet}}$ → (Fe, Mg, Mn)$^{\text{oct}}$ + (OH$^-$)) with a greater phengitic component (and lower A$^{\text{oct}}$) in micas with longer wavelength, consistent with the expected relationship between wavelength position and chemical composition (Post and Noble, 1993; Duke, 1994; Swayze et al., 2014; Yang et al., 2011).

Using 159 EPMA spot analyses from 14 separate areas on three thin sections for which analysis locations were logged and average white mica wavelength positions from corresponding locations on billets (excepting 14HYPORH013a-Billet 2), a significant linear relationship ($r^2=0.77$, p<0.01) was calculated (solid line in Figure 9). For comparison, the equation of Swayze et al. (2014), computed using high resolution Fourier-transform infrared (FTIR) spectra, is also shown in Figure 9 (dashed line). The lines parallel one another but the data from our study has the line shifted to a higher A$^{\text{oct}}$ value for a given wavelength. A strong linear trend is clear in the data for the Orange Hill samples, although the coefficient of determination from the linear regression is lower than that reported by Swayze et al. (2014) and is possibly explained by slight variations in mineralogical composition between billet and thin section weakening the correlation.

Figure 9: Scatterplot of white mica wavelength positions from Corescan billets and average A$^{\text{oct}}$ from electron probe microanalysis (EPMA) on corresponding locations on thin sections (diamond symbols). The linear regression line for Orange Hill samples is shown with solid black line. For comparison, the linear relationship based on A$^{\text{oct}}$ from x-ray fluorescence (XRF) measurements for reference samples of muscovite and illite from Swayze et al. (2014), modified for wavelengths in nm, is shown with dashed line. A$^{\text{oct}}$ was computed from EPMA data with assumption of all iron in the Fe$^{2+}$ oxidation state for Orange Hill samples and from XRF data with assumption of all iron in the Fe$^{3+}$ oxidation state for most samples in Swayze et al. (2014).
The offset in lines in Figure 9 is likely a result of the manner in which iron oxidation state is treated in the computation of muscovite cation numbers using data from EPMA versus XRF. For EPMA (used in this study) all iron is assumed to be Fe$^{2+}$ whereas for XRF data for the reference muscovite and illite samples in Swayze et al. (2014) all iron is assumed to be Fe$^{3+}$, with the exception of a few reference samples that have values for Fe$^{2+}$ and Fe$^{3+}$ derived from wet chemistry. EPMA analysis of reference samples GDS114, GDS116, GDS117, and GDS118 from Swayze et al. (2014), overlapping the Al of the Orange Hill samples, result in higher Al oct values for three samples compared to previous XRF-based numbers (the increase ranges from 0.026 to 0.096 higher in Al oct), while one sample, GDS118 has slightly lower Al oct, by 0.028. Dependent on the manner in which other samples are analyzed (EPMA versus XRF) and lacking Fe$^{2+}$/Fe$^{3+}$ data from wet chemistry, the different assumptions in the treatment of iron for computing muscovite cation numbers will affect whether Al oct and wavelength values plot closer to the line established in this study or that in Swayze et al. (2014).

**DISCUSSION**

**Comparison of mineral information at different scales**

The three measurement levels (airborne, field, and laboratory), produce mineral maps that identify the same set of spectrally predominant mineral classes, specifically, white mica, clinochlore+white mica, chlorite/clinochlore/epidote, kaolinite, kaolinite+white mica, mixed layer clay (illite/smectite), and gypsum (compare Figures 3, 6a, and 7). The identification of these minerals is supported by the XRD results (see Table A2 of Graham et al., in press), which confirm variable proportions of the same minerals identified spectrally and do not indicate the presence of other spectrally detectable minerals. The multiscale hyperspectral study by Kruse et al. (2012) of an inactive silver mine with spectrally predominant illite-muscovite, jarosite, and kaolinite, also showed similarity in mineral mapping results across the three levels of collection. That study relied, in part, on data interpreters to interactively select reference spectra from the imagery at each collection level and assign mineral classes. The fully-automated MICA analysis in this study used a single set of mineral reference spectra from an independent source library to map minerals in the data spanning the three scales. Mineral predominance mapping was primarily focused on non-iron bearing minerals with diagnostic absorption features in the longer wavelengths (1500 to 2500 nm). Surface coatings from weathering in this study area, principally hematite, goethite, and jarosite, on rocks imaged with airborne and field-based spectrometers have the strongest influence on the shorter wavelengths (400 to 1500 nm) and did not cause appreciable difference in mapped classes of predominant minerals compared to images of cut rock surfaces measured in the laboratory.

For the outcrop scan at Orange Hill, white mica wavelength position maps from HySpex data show consistent trends with HyMap data, both revealing shorter wavelength positions in the southern portion of the hill (right edge of Figure 6b). Although the HyMap-derived wavelength positions are shifted approximately 1nm to shorter wavelengths (cooler colors) compared to HySpex, it is important to remember that the coarser bandpass of HyMap compared to HySpex is expected to cause an approximately 1 nm shift to shorter wavelengths. Thus, the HyMap and HySpex results agree within anticipated differences. The white mica positions from the Corescan imaging spectrometer data for the rocks collected from the Orange Hill deposit (Figure 7b) are generally more comparable with the wavelength classes (warmer colors) of the HySpex results (Figure 6b). This consistency is dependent on the shifting of the Corescan imaging spectrometer data by 1.4 nm to longer wavelength, which was done based on the evaluation of reference standards (see the Methods section). Considering spectrometer differences, wavelength positions are comparable across the three measurement levels, revealing similar trends in white mica from shorter (2199 nm) to longer (2207 nm) wavelength position. The recognition and quantification of subtle spectral differences among spectrometers permits data leveling and comparison of absorption feature positions across instruments and different spatial scales.

**White Mica Wavelength Position and Al Composition**

Graham et al. (in press) suggest the widespread long wavelength absorption feature positions for white mica may be consistent with either a deep level (potentially below the ore shell) or distal fringe exposure of the deposit. These porphyry fluids would be near neutral versus acidic to form phengitic micas, as suggested by Halley et al. (2015) for an idealized porphyry deposit model. However, the additional clinochlore+white mica signature and high Cu, Mo and/or Au in sediment samples draining areas with longer wavelength white mica would argue against weakly mineralized distal fringes, and instead may reflect the high grade core of the system. This interpretation by Graham et al. (in press) is by analogy with reported studies at Pebble, Alaska, Bingham, Utah, and Red Chris, British Columbia (Harraden et al., 2013; Parry et al., 2002; Norris, 2012; respectively) that show long wavelength positions of white mica in wide alteration zones produced by relatively low temperature fluids that overprinted earlier alteration minerals. At Pebble, Harraden et al. (2013) found a greater magnitude of wavelength shift, with sericite of the phyllitic assemblage overprinting the potassic core having wavelength positions $\geq 2215$ nm. Regardless, the phengitic compositions of the micas associated with porphyry deposit formation are, on the whole, sufficiently compositionally different to produce distinctly longer wavelength white mica absorption features relative to rocks unaffected by magmatic-hydrothermal fluids. As observed for the porphyry in this study, white mica wavelength position maps from airborne imaging spectrometers can be used to better understand hydrothermal systems (Swayze et al., 2014; Yang et al. 2011) and, potentially, as a vector to ore in deposit types that can have large alteration footprints, including epithermal (Bierwirth et al., 2002), iron oxide-copper-gold (Laukamp et al., 2011), and volcanicogenic massive sulfide (VMS; van Ruitenbeek et al. 2012).

**Mineral Signatures Unique to the Laboratory Level Data - Molybdenite**

Laboratory level imaging spectroscopy reveals additional important mineral information that is difficult to obtain in relatively coarser scale data. During an examination of the spectra of pixels that did not match any of the 77 reference spectra, two absorption features in the visible wavelength region (centered
near 584 and 654 nm) were found to be consistent with the presence of molybdenite on the surface of the samples. These spectral features are similar in position and shape to features found in a reference sample of molybdenite (Ward Scientific sample from Knabenheim, Norway, see Figure 10a), with the absorption features arising from electronic transitions (Evans and Young, 1965). Using two spectra from 15HYPORH002 as the reference spectra in a MICA analysis, an image of the distribution of molybdenite in Orange Hill rocks was generated. Figure 10b shows the molybdenite map for sample 15HYPORH002, which is consistent with visual observation of molybdenite and confirmation of molybdenite in this sample by XRD. Molybdenite was also spectrally identified in three other rock samples from Orange Hill.

The molybdenite detection demonstrates that the laboratory level imaging spectroscopy reveals additional important mineral information that is difficult to obtain in coarser scale data, due to low mineral abundance or oxidative coatings at the ground surface. Additional mineral information may also be derived at the laboratory level of imaging by detecting absorption features in wavelength regions typically obscured in field and airborne data by atmospheric gases, specifically, the 1400 and 1900 nm regions that are affected by atmospheric water vapor. For example, Turner et al. (2017) used these regions to discriminate between muscovite, prehnite and zeolites in laboratory hyperspectral images of sapphire-bearing marble.

Laboratory imaging spectroscopy in the visible to SWIR (VSWIR) wavelengths suffers from some of the same limitations encountered at other imaging levels, in that some minerals (many of the primary rock forming minerals such as quartz and feldspars) do not have diagnostic absorption features. For example, the quartz vein in sample 15HYPORH018b was not matched to any reference spectra by the MICA analysis because spectra in the vein lacked absorption features over the VSWIR range (Figure 7a). Mapping of minerals lacking absorption features has been attempted by user-selected, site specific, endmember spectra and user-defined thresholds on reflectance level and slope (e.g., delineation of “aspectral” regions in The Spectral Geologist, https://research.csiro.au/thespectralgeologist/wp-content/uploads/sites/128/2016/12/tsg8_whats_new.pdf); such methods require that thresholds on reflectance level and slope parameters be determined for each data set because these parameters are affected by a range of minerals, grain size effects and measurement conditions. Furthermore, thermal infrared (TIR) imaging spectrometers covering the longer wavelengths, where these minerals have strong absorption features, are being advanced for airborne, field and laboratory level investigations (Bedell, et al., 2017). TIR offers the potential for collection of supporting mineral information (e.g., observation of absorption features in the TIR for a mineral with SWIR features; Tappert et al., 2013) or new mineral information (e.g., observation of absorption features in the TIR for a mineral that does not have SWIR features; Tappert et al., 2015).

**Imaging Spectroscopy at High Latitudes**

To our knowledge, the study of Orange Hill-Bond Creek deposits, reported here and in Graham et al. (in press), is the first published application of airborne imaging spectroscopy for geologic or mineral studies in Alaska. Compared to mid-latitude deposits, collections of airborne imaging spectrometer data at high latitudes are fewer and most have been published recently (Bedini, 2009 and 2012; Black et al., 2016; Laakso et al., 2016; Rogge et al., 2014; Tukiainen and Thomassen, 2010). Difficulties that likely inhibit such studies include the narrow seasonal window with adequate illumination and the requirements for clear weather during collection and some degree of exposure of bedrock, or at least in situ regolith (Bierwirth et al., 2002). However, despite the rugged, poorly illuminated terrain we encountered in Alaska, both the airborne and field imaging spectrometer data we collected were adequate for establishing distributions of spectrally predominant minerals and identifying subtle changes in mineral chemistry that characterize known porphyry deposits.
Our study focused on analysis of spectral features in areas of exposed rock and sediment with diagnostic mineral absorption features. However, many deposits (e.g., Orange Hill) are largely covered by vegetation, follow-on studies should examine spectral signatures of vegetation and soils within mineralized versus non-mineralized areas. Variations in soil nutrient and cation content related to underlying geology have the potential to lead to variations in vegetation cover density, species composition, and biochemical concentrations (pigments, nitrogen, lignin, cellulose), resulting in contrasting vegetation-related spectral signatures (e.g., Swayze et al., 2009) that could be used to more completely define boundaries of mineral deposits.

In this study, using a HySpex SWIR sensor to image a poorly illuminated surface with collection time limited by clouds and rain, we were able to produce maps of predominant minerals at 90 cm spatial resolution and white mica wavelength information that could be used to more completely define boundaries of mineral deposits.

For accessible areas, field-based imaging spectroscopy is a potential alternative to more expensive regional coverage from airborne imaging spectrometers. In this study, the HySpex sensor, associated heavy duty tripod and motorized scan head, controlling computer, and other accessories were transported in a moderate payload capacity helicopter (Jet Ranger) and fit in a large sport utility vehicle. A significant challenge to wider application of imaging spectrometer data from an aircraft. For example, the day we collected the Orange Hill scan, a large tarp had to be used to protect the instrument during intermittent periods of light rain. For accessible areas, field-based imaging spectroscopy is a potential alternative to more expensive regional coverage from airborne imaging spectrometers. In this study, the HySpex sensor, associated heavy duty tripod and motorized scan head, controlling computer, and other accessories were transported in a moderate payload capacity helicopter (Jet Ranger) and fit in a large sport utility vehicle. A significant challenge to wider application of imaging spectrometer data from an aircraft. For example, the day we collected the Orange Hill scan, a large tarp had to be used to protect the instrument during intermittent periods of light rain.

Despite the potential for collection of field-based imagery on marginal weather days, many months of the year lack sufficient solar illumination for data collection at high latitudes. Several of the commercially-available imaging spectrometers can be interchangeably mounted on tripods for field collection and over translation stages for laboratory level scanning of geologic samples. The ability to scan materials indoors during the winter months could allow imaging to be done year-round.

CONCLUSIONS
This study demonstrates that imaging spectroscopy (hyperspectral imaging) can be used to identify porphyry copper-related alteration and mineralized rock in a remote part of Alaska. Spectrally predominant mineral and white mica Al-OH absorption wavelength maps are consistent across airborne, field, and laboratory scales of imaging spectrometer data. The more phengitic white micas, with wavelength positions exceeding 2203 nm, as established by linking the laboratory level spectra with Al composition from electron probe microanalysis, are attributed to magmatic-hydrothermal activity. Longer wavelength white micas coincide with the clinactinolite-white mica assemblage in the Nabesna pluton and altered volcanic rocks at Bond Creek. Geochemical results for samples collected to investigate white mica wavelength anomalies, north of the main porphyry deposit cluster, confirm elevated Cu, Au, and Mo indicative of previously unrecognized mineralized rock. The geologic and tectonic settings of mountainous regions in Alaska with significant exposure are permissive of (and in some cases known to host) a number of deposit types (e.g., VMS and orogenic and intrusion-related Au systems) that may have large alteration footprints. Imaging spectrometer data collected from simple drill core and outcrops, or by aircraft for regional study, have the potential to assist in defining these footprints. This study and a growing body of literature applying imaging spectroscopy to geologic investigations provide support for utilization of the technology for informing mineral exploration elsewhere in the state of Alaska as well as other areas at high latitudes. Imaging spectroscopy studies conducted in these remote areas based on airborne imaging, field scans, or laboratory level imaging of samples or drill core, could provide direction for follow-up sampling and investigations and reduce subsequent exploration costs.

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